The Use of Water-filled Bags to Reduce the Effects of Explosives.

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Introduction

This paper describes work by Dell Explosives and Edinburgh University on the suppression of the effects of explosions by water bags. Four fields of application are considered. Details of practical construction, the physics of suppression, deployment and the psychology of irritating noise are discussed.

Fields of Application

1. **Civilian Building Demolition**

   It is now considered desirable that some of the high rise apartment blocks built in Britain during the 'sixties should be demolished. They are often close to other buildings so that there is danger from blast fragments and nuisance from dust. Reducing these is of greater importance than reducing noise which provides the crowds of spectators with pleasure and excitement. Explosives are usually placed in vertical walls and columns. Labour costs and the problems of gaining safe access to high outside walls are important.

2. **Disposal of Surplus Stored Munitions**

   Enormous quantities of military explosives are no longer needed. It is expensive to guard them and to move them to the most remote disposal sites. Controlled burning may cause more pollution and can lead to inadvertent high-order explosions. Time pressures are not great, anti-handling devices will not be active, items will be in reasonable condition and well identified. The disposal site can be chosen and excavation is possible. Operations can be planned so that long storage life of the suppression equipment is not essential. However the quantities of explosives are enormous and the civilian irritation threshold for a long series of repeated explosions at random times is very low. The objective is to obtain maximum reduction of long-range noise and ground-shock with minimum cost.

3. **Disposal of Used but Unexploded Weapons**

   A substantial fraction of the explosives used in wars fail to operate properly and are found decades after the end of hostilities. People in France are still being killed by explosives from the 1914-18 war and even a few in America from the civil war. There is no particular time pressure and nobody would complain about noise. However there is no control of the site and the distances to adjacent properties may be very short.

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Screw threads will be heavily corroded. The internal details of very old weapons may be obscure and anti-handling devices may still be active. An effective method of blast suppression provides the disposal officer with a useful, extra option. Cost is of relatively little concern but a long storage life, high reliability of the suppression mechanism and accurate property-damage prediction is of great importance. We need a versatile set of equipment which can be adapted to a wide variety of unpredictable situations.

4. **Suppression of Terrorist Bombs**

Terrorists can achieve their objective with quite small quantities of explosives but choose particularly expensive targets. They very often fit anti-handling devices and try to evolve new designs. If suppression methods are to be successful they must have extremely short deployment times - a very few minutes - preferably with no requirement for close personnel approach. They should suppress damage and injury rather than noise. They should allow inspection of the device and the use of disrupter equipment. They must operate despite obstruction to access by parked cars. Terrorist bombs can be very expensive in life, property and political embarrassment so that the cost of effective suppression equipment is of much less consideration than its speed of deployment. This would have to be reduced to a few minutes but times as short as this may be achievable if equipment is prepositioned at sensitive sites.

The four applications listed above lead to quite different designs for suppression. Our team have considered them all. Keenan and Wager (1992) have reported on a fifth application, that of a permanent water enclosure placed round explosives in magazines so as to reduce the damage from accidents and also the land requirement for danger zones round explosive storage facilities.

Distinctions

It may be helpful to dispel some possible misunderstandings. Firstly water-bags packed closely round an explosive do very much more than merely presenting the mechanical obstruction which could be obtained from an equal weight of sand bags.

Secondly the speed of finely dispersed water drops thrown out from the explosion is very much lower than the speed from a water jet disrupter. In the latter a small but 'solid' slug of water is driven at supersonic speeds by a confined charge and the transfer of explosive to kinetic energy is fairly efficient.

Thirdly the behaviour of an explosion in a lenticular package of water bags of the order of a metre thickness all around the charge is different from that of an explosion deep in a large body of water. In the latter case the water presents a very large inertia to the gas products in the horizontal direction and the explosion bubble growth depends on the compressibility of water. The bubble expands as a sphere with very little mixing of gases and water. Moderate depths of immersion allow a slug of water above the explosive to be thrown vertically

upwards in a narrow column while horizontal movements remain largely suppressed. The system behaves like a very large calibre mortar. With water bags we are trying to achieve as much mixing of the explosion gases and water as we can.

The Observations

Experimental work to date has been privately supported and has had to use targets of opportunity with improvised instrumentation. Nevertheless the results are so striking that we hope delegates will forgive their anecdotal nature.

We were offered two identical reinforced-concrete wall-partitions in a nuclear command bunker. We drilled holes for charges and placed target boards opposite them. A board 4 metres from the protected wall was unmarked by the explosion debris. The unprotected one had fist size penetrations over half its area. Concrete fragments on the unprotected wall were scattered all over the bunker with many impacts on the opposite wall and ceiling. Most of the material on the protected side was deposited in a neat pile close to the foot of the partition.

In a second experiment in a quarry we protected one side of a concrete block leaving the other side exposed. We placed scrap cars with opened doors at 10 metres on either side. The explosion of 6 borehole charge in the centre of the block sent concrete fragments clear through the car on the unprotected side emerging from the trunk. None of the windows of the car on the protected side was damaged. Concrete fragments were found at distances up to 110 metres on the unprotected side but only 6 metres on the protected one.

In an open field trial we compared a protected blast of 10kg of Gelamax with 1kg of an unprotected one. At a range of 150 metres down wind (about 5m/sec) using a Bruel and Kjaer 2218 sound level meter (which records down to 50 microsecond rise times) we measured 136 dB with linear weighting for the 10kg charge and 139 dB for the 1kg one. Ten times the charge weight produced 3 dB less pressure. Three experienced explosives engineers thought at first that the protected charge must have misfired. A pair of Anderson paper gauges at 6 metres from the 1kg charge had burst panels corresponding to 4.1 psi (28.2 kPa) but the 0.9 psi (6.2 kPa) panel was unmarked on the protected 10kg charge. The furthest fragment of earth from the protected charge was thrown 14 metres but the crater diameter was 2.75 metres, about 50% greater than expected.

We have also been collecting anecdotal accounts of the effect of water. For example Byers (1994), tells of reductions in the effect of explosions in snow and long wet grass. Quarrymen have noted the reduced effect of explosions in the blasting of wet rock strata.

Materials

Polythene sheet is available in a range of densities from 0.91 to 0.96 according to the amount of the cross bonding between molecular chains. It is extremely cheap with a cost of about $1.90 per kilogram independent of density. The tensile strength and hardness increase with density but the range of yield and the ability to survive sharp folds reduce. Our work to date

uses a material with a yield stress of 17 MPa (~ 2500 psi).

A very popular form of supply is the 'layflat' tube. The wall thickness can range from 40 microns (0.0016 inch) up to 2mm for layflat dimensions up to 17 metres. Manufacturers can very easily change width and wall-thickness to suit particular requirements. Most of our work has used 250 micron thickness with a layflat dimensions of 0.76 metres. This inflates to a flattened cylindrical shape with a nominal diameter of 0.484 metres and would yield at an internal pressure of 17.5 kPa (~2.5 psi) corresponding to a head of water of 1.8 metres. It costs 70 cents a metre length (~20 cents/foot). We work happily with heads of 1 metre and would want to check corner-fold resistance and low temperature properties carefully before going to a higher density or thicker material.

Some rolls suffer from small pin-holes leading to slow loss of water which will be insignificant over the times of deployment. Damage is easily caused to the edges of a roll if it is carelessly dragged near the vertical on a rough floor. Careful supervision of warehouse and delivery staff is desirable. Making a deliberate round pinhole to a pressurised bag does not lead to sudden failure. This may be because of the very long range of local yielding which reduces the stress concentration.

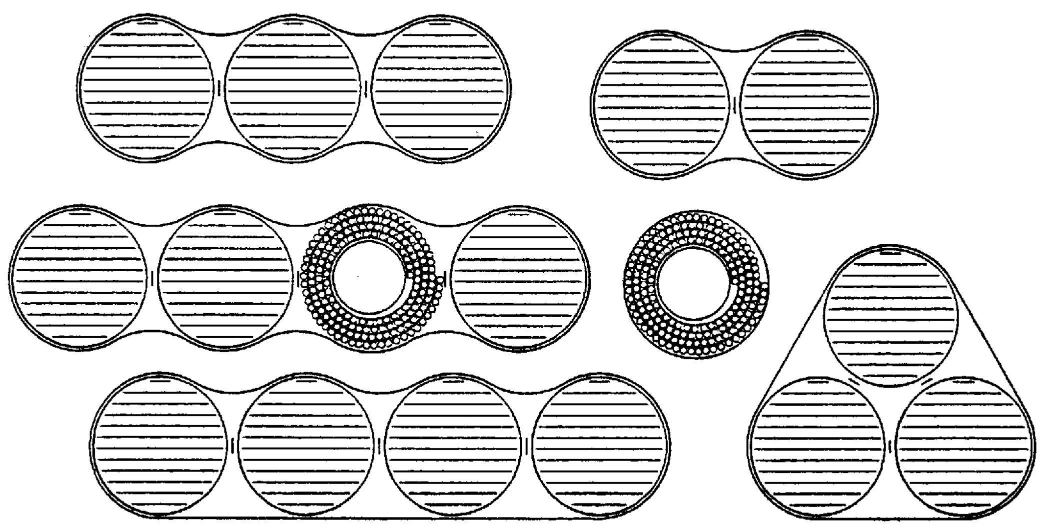
In some applications we might consider the use of much stronger and much more expensive materials with textile reinforcement. An example has a layer of nylon bonded to a layer of polyurethane. This is used for waterproof clothing and has excellent resistance to abrasion. A rather thin sample, only 300 microns thick, can take a membrane tension of about 20,000 N/metre width but at a cost of about $10 per square metre and a safe extension of only 20%. Thicker materials with strength in proportion are widely available. There is a wide range of polythene welding equipment available, purpose designed for heat-sealing food, laboratory specimens, shopping bags etc.. With improvised welding tools a bag can be made in a few minutes. With a moderate investment this time can be reduced to a few seconds.

Handling and Erection

Because of pumps, hoses and taps, water is much more convenient to transport, pump to height and dispose of than sand bags. Although polythene layflat tubing offers a very cheap and sufficiently rugged way of holding water, the partially filled bags can be extremely difficult to control. Those delegates to this conference who have tried to get drunken Sumo wrestlers into an elevator along with anaesthetised bull-elephant seals will understand the problem except that the bags offer no wrists, ankles, loin-cloths or flippers on which you can get a firm grip. It is no easier to drag two tons of water than two tons of scrap iron. However the reluctance of the bags to slide on level ground is matched only by their determination to roll down the most imperceptible incline. Only a short bag filled to tautness with square 'pillow-case' ends offers any roll stability. Long, partially filled bags can roll in several directions at once. The rule is that bags must be in the right place before water is admitted and that methods for keeping them in place must be carefully engineered. One bare tube will always roll off another. Single bags can be effective if the lie of the land is suitable but they give thin coverage to the top of larger charges.

Stability can be provided by enclosing two or more tubes in a common casing as shown in figure 1. Rolling would require relative motion between adjacent members. This is prevented by friction due to the pressure along the contact line. It can be further increased by welding or by an adhesive such as double-sided tape. The equilateral triad requires careful pre-arrangement and filling if the top member is not to flop down between the other two. However once the outer casing is taut, the group is quite stable even on sloping ground. Three men can jump on the top. Triads are a good way to build height which is needed to cover larger charges.

Figure 1. Casing two or more tubes in a common outer sheet provides stable building elements which can be stacked round many shapes of charge.



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The tensions in the outer casing will share the load and so reduce those of the inner bags. This does not help material near the 'hemispherical' ends of the inner tubes but this region experiences stresses which are half those of the hoop stress in the cylindrical region. If the circumferential length of the casing is correct we can nearly double the safe head and achieve nearly constant stress in all directions of the layflat. In addition to the triad, flat groups of two or more tubes can interlock with one another and so also be used to build walls as shown in figure 2.

Figure 2. A typical stack including air spaces to increase surface area and delay the shock fronts. Very small gas volumes have a profound effect on the speed of sound.

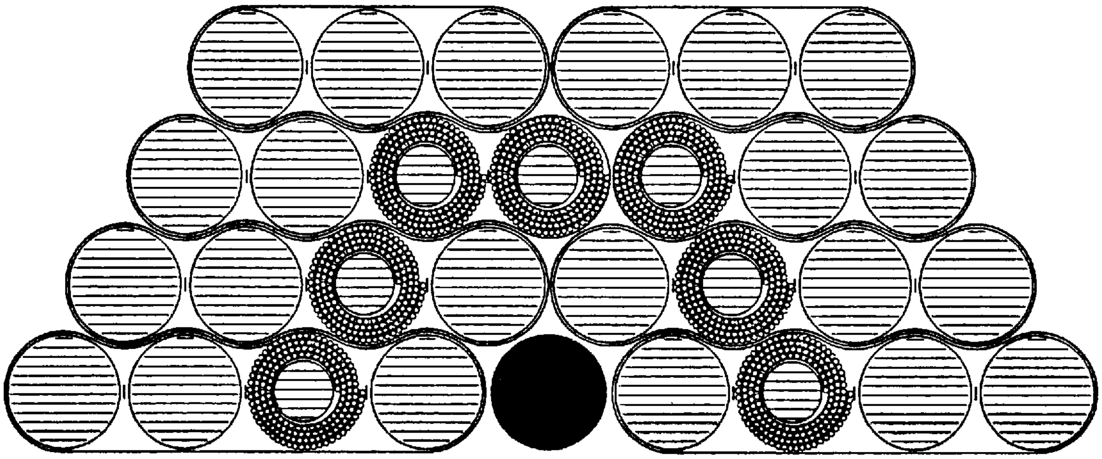

Figure 2. A typical stack including air spaces to increase surface area and delay the shock fronts. Very small gas volumes have a profound effect on the speed of sound.

For suppressing blasts from the demolition of buildings the essential problem is that much of the blasting takes place in vertical walls and columns while water likes to be horizontal. Cheap bag materials can take internal pressures corresponding to one, or perhaps just two metres water head but this is not really enough. We do not want the trouble of filling many separate small bags, especially if these are protecting outside walls.

A solution is the use of a cascade in which a long length of layflat tube is looped over a series of meshes of a net or the horizontal rungs of a grid made of rope and PVC piping as shown in figure 3. A length of layflat is sealed at the bottom and water is pumped into the top. When the level of water in the first loop reaches the highest mesh it overflows to fill the second and so on down the cascade. By choosing the loop length and mesh spacing we can cover a large vertical range while keeping the pressure in each loop within the safe limit of polythene. In contrast to sandbags, the weight of netting and plastic tubing is low enough to be handled by people on ladders or hoisted by hand from the ground. In the last resort it is more comfortable to have a bag of water dropped on your head than a bag of sand.

Figure 3. A sectional view of a cascade of water bags on the meshes of a net.

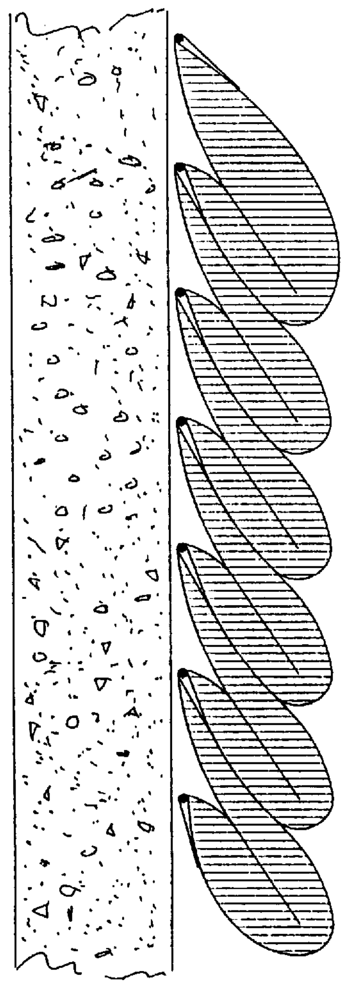

Figure 3. A sectional view of a cascade of water bags on the meshes of a net.

Some applications, particularly those involving the suppression of car bombs, may require the bridging of explosives without any contact with them. At first sight water bags do not seem attractive for the construction of beams, arches or slender columns especially as they have no rigidity until the skin is taut and they must go through a long phase of non-tautness beforehand.

It is however possible to get round the problem. The first step would be to pump water into the base of the structure so as to provide a gravity base and prevent it from being blown about

by the wind. The next step is to inflate a second set of cased bags to tautness with air or exhaust gas, which gives a stiff but very light structure with a shape defined by the casing. Water would then be pumped into the structure to replace the gas, which would be vented off through pressure-relieving values at the top. A programmed sequence of gas and water filling can produce quite complicated structures such as the one shown in figure 4. We hope to build one soon.

Figure 4. The filling sequence for a structure of columns and a beam.

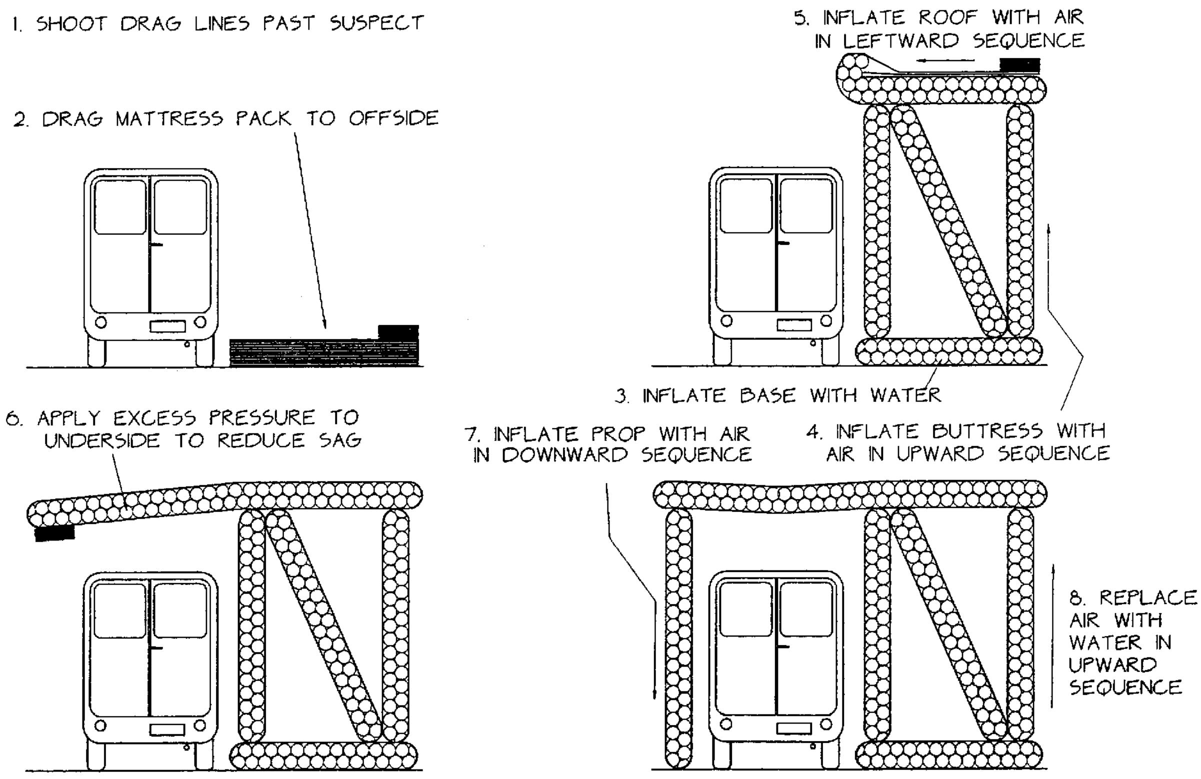

Figure 4. The filling sequence for a structure of columns and a beam

The design rules are that a simply-supported beam made of cased bags will not collapse if the tension in the upper skin of the casing remains positive and the tension in the lower skin does not exceed its strength. With strong casing materials using textile reinforcement, spans of a few metres can be achieved. Larger gaps can be supported with the help of solid materials such as polystyrene foam which will not present fragmentation hazards.

Plumbing

There are three options for connecting groups or sub-groups of bags. We can arrange them

within a casing in a multiple Z-fold and fill them sequentially from one end. This requires the least number of hose connections but it can take a long time for water to get round the bends of a Z-fold and attempts to force it too quickly can burst the first bag. The Z-fold system must be filled slowly.

Although layflat tubing is very cheap it does not offer convenient connections to hoses, which are needed in larger numbers for parallel filling. We are most reluctant to use any hard or heavy hose fittings because we grudge their cost, because we want flat packing and because we do not want hard fragments thrown out by the explosion. A parallel connection can be made by joining two bags with glue, hot welding or patches of double-sided adhesive and then punching holes within the area of the patch. This can be done with a stack of many tubes.

It is convenient for training and experimental work to fill and empty individual bags and it can also be useful to control the amount of air in them either by bleeding off excess dissolved gases often found in hydrant supplies or by deliberately adding extra air to some tubes. The entry mechanism should allow bags to be stacked flat or rolled for compact transport.

A suitable design shown in figure 5 is to cut the layflat tubing along an oblique line leaving a fillet to a short tongue about 120mm wide. The bag is then welded along the cut leaving the square end of the tongue open. A length of much narrower layflat with a retaining strip of double-sided adhesive tape is then passed inside the tongue and the tongue ends are sealed around it. Any pressure inside the bag will close the narrow layflat but it can be opened by the insertion of a hollow probe. The seal is not quite perfect but the leakage rate for water is acceptable and the leakage rate for air can be kept to the same value by having the entry at the lowest part of a bag and putting in some water with the air.

Figure 5. The non-return valve and welding detail of a layflat tube.

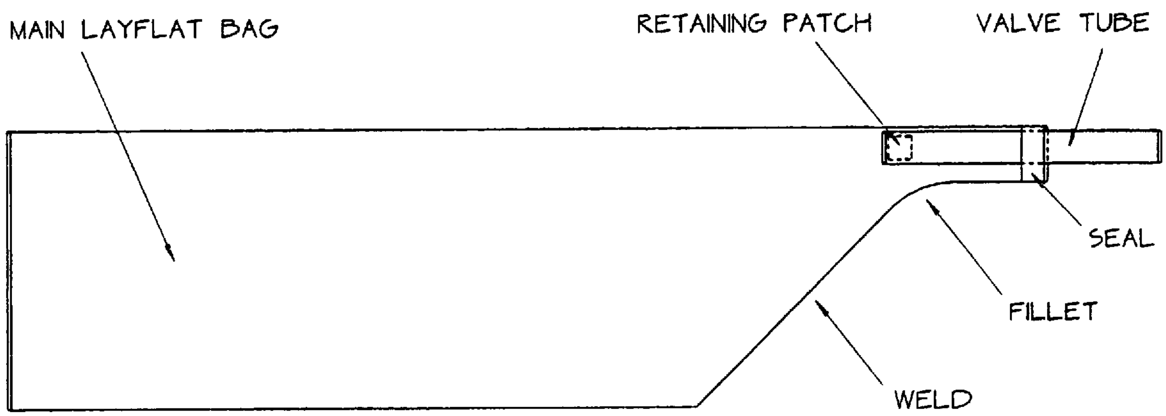

Figure 5. The non-return valve and welding detail of a layflat tube.

In urban applications bags will often be filled from fire hydrants which can supply water at pressures far greater than the bags can resist. A convenient pressure limiter can be made by using an open vertical PVC pipe about 200mm in diameter with a height corresponding to the required relief pressure. This will also remove gas bubbles from the water stream. These may be wanted in bags near the charge but not in those furthest away.

Shock Wave Velocities

The behaviour of explosives and the transmission of shock waves through air and through water have been the subject of intensive study for many years and the results are now well known (see, for example, Taylor (1946) and Cole (1948)). Except in the region very close to the explosive charge, the velocity of propagation of a shock wave depends on the square root of bulk modulus over density. For water this is about 1500 metres per second. For a gas the bulk modulus is the product of pressure and the specific heat ratio (1.4 for air). Both the density and the bulk modulus of a gas rise directly with pressure so this has no effect on the speed of sound. Temperature changes at constant pressure do change the density and so the speed of sound rises with the square root of absolute temperature. At 0°C the velocity in dry air is 331 metres/sec. At 3000°C, about 11 times hotter on the absolute temperature scale, it would be 3.3 times faster i.e. 1100 metres per second. Higher speeds occur for the lighter gases like carbon monoxide and steam which are produced by explosions.

Things get more interesting if there are bubbles of air in water or drops of water in air. If these are small compared to the wavelengths of sound, the air bubbles give great reduction of bulk modulus but not so much in the density. Karplus and Clinch (1964) have shown that a

very small amount of air in water or water in air has a profound effect on the speed of sound. Their results are plotted in figure 6. The curve is a flat-bottomed U-shape with values close to 25 metres per second for air-to-water volume ratios of 20% to 80%. The velocity *c* for any proportion *x* of water to air can be calculated from the Karplus equation

EQUATION

$$\frac{1}{c^2} = \frac{x^2\gamma}{c_G^2} + \frac{x(1-x)}{P}\rho_L + \frac{1}{c_L^2}$$

Shock waves with the magnitude of explosions will of course squash the bubbles to very small volumes but the water around them has to be given kinetic energy to move into the bubble space and then again when the bubbles bounce back. Furthermore squashing bubbles makes the air in them very hot and so water can be evaporated. There is also the interesting result that the back of the shock wave, where compression has reduced the volume of bubbles, ought to be travelling faster than the front where the bubbles have not yet been compressed. This makes for very high pressure gradients which are associated with large internal losses.

We would achieve some very interesting hydrodynamic behaviour if it were possible to release something like powdered Alka-Seltzer tablets evenly through the water bags a short time before a charge is exploded. Until our chemists can do this we have to rely on physical bubble placement. Fortunately the use of multiple-bag construction allows a way to do so.

The fraction of interstitial space between close-packed cylinders in a hexagonal array is

EQUATION

$$\sqrt{3} - \frac{\pi}{2} \approx 0.161$$

Figure 6. The Karplus and Clinch results for the speed of sound as a function of the fraction of air to water. The pressures of explosions will have to accelerate the water in order to squash the bubbles. This compression will make the air very hot.

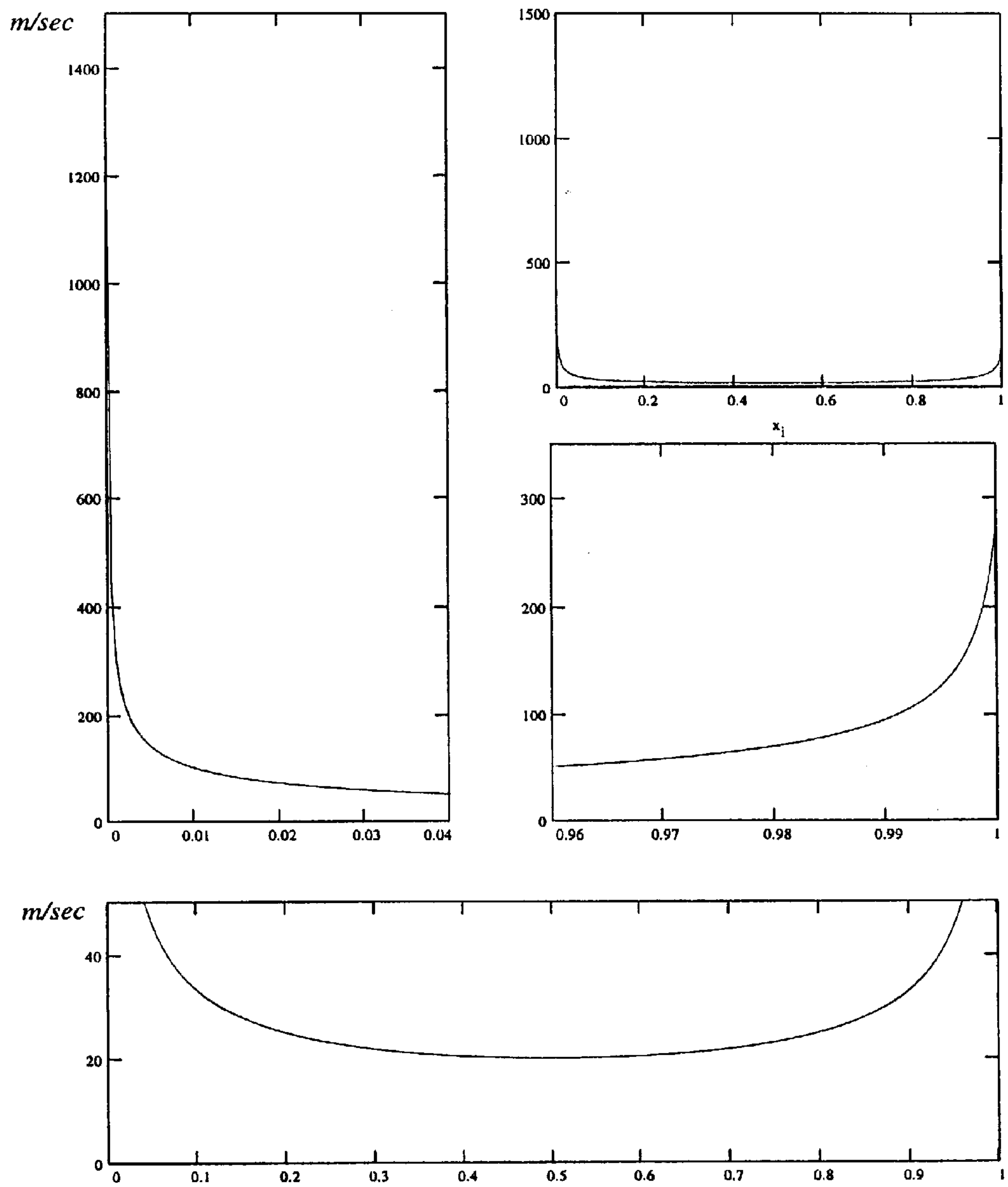

Figure 6. The Karplus and Clinch results for the speed of sound as a function of the fraction of air to water. The pressures of explosions will have to accelerate the water in order to squash the bubbles. This compression will make the air very hot.

This will be reduced if non-rigid water bags bulge into the interstices but we can still expect about 10% of included air.

This percentage can be increased using another polythene product known in the UK as bubble-pack. It consists of a dimpled layer of polythene bonded to a flat layer. Typical dimples are 25mm diameter cylinders 10mm deep. By enclosing rolled up bubble-pack in water bags or by wrapping bubble pack round them we can increase the fraction of enclosed gas as much as we desire. The best fraction is not yet known but 20% to 30% for the region near the explosive seems a reasonable guess. Larger gas fractions can be included by the injection of nitrogen from gas cylinders or gas from the exhaust of a support vehicle into selected bags.

As we want to achieve lots of mixing between gases and water, with room for the water to break up into small drops with a large surface area, we should increase the air to water ratio at a chosen distance from the explosion. This can be arranged by packing air bags or bubble-bags as in figure 2. Note that lines drawn from the centre of the explosion pass through alternating water, air and then water compartments. The air space is meant to be a mixing chamber close enough to the charge for temperatures and pressures to be high but with space enough for the separation of water drops. Any pair of paths with different speeds of particle movement should produce vortices which are good for local energy dissipation and for helping the mixing processes.

Fragment Velocities

We can distinguish two very different cases for the velocities of explosion fragments. In the first, studied for example by Taylor D B and Price (1971), the casing is of comparable mass to the explosive as in a shell, bomb or gas storage vessel. Energy goes to accelerating the fragments, to forcing gas through the gaps between them and to expanding the gas. Very little is lost in breaking the casing. This is very different from the case of quarry blasting where the mass of rock is much greater than that of the explosive and the intention is to do work on breaking up the rock. This has been studied by Roth (undated).

According to Taylor and Price, the highest fragment velocities of parts of light casings will be up to 2.236 times the velocity of sound in the contained gas before fracture. The product gases of explosions are carbon monoxide and steam with about half those quantities of nitrogen. The first two have significantly lower densities and consequently higher sound velocities than air. The speed rises with the square root of absolute temperature and so we should expect fragment velocities up to 4000 metres per second. Elongated fragments with low drag coefficients like nails can travel great distances. The fragment range and fragment kinetic energy depend on the square of velocity.

The Gurney formula discussed by Roth predicts that quarry fragment velocities from the detonation will be

EQUATION

$$V = \frac{D}{3}\sqrt{\frac{c}{m}}$$

where *D* is the detonation velocity of the explosive and *c/m* the charge-to-rock mass ratio. Detonation velocities for most explosives are in the range 5000 to 9000 m/sec.

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The addition of a mass of any substance many times heavier than the mass of the charge produces a direct reduction in fragment velocity, provided that this mass is placed evenly round the charge and does not provide partial confinement like that of a gun.

The analysis of video sequences of suppressed explosions shows ragged sharp-edged fronts of the escaping water and so allows approximate velocity estimates. These are much lower than for the equivalent weight of sand bags, especially for water moving at angles between the horizontal and 45 degrees. It might be possible for a casing fragment to move faster than the water around it but it would then be subject to drag forces about 800 times higher than for a passage through air.

Thermodynamics

The amount of chemical energy in an explosive is larger, but not very much larger than the amount needed to evaporate an equal weight of water. Values range from 3.7 megajoules per kilogram for ANFO through 4.5 for TNT to 7.5 for materials like Torpex which include powdered aluminium. It takes 0.33 megajoules to raise the temperature of a kilogram of water from 20 to 100°C and then a further 2.26 to turn it into steam. This means that the range of explosive to evaporation energy ratios is only 1.5 to 3. It is not difficult or expensive to provide water-to-explosive weight ratios much greater than this. The problem is that the evaporation must happen in the millisecond time scales of explosions.

The designers of heat exchangers use heat transfer coefficients measured in watts per square metre degree centigrade. The very best equipment can exceed 20,000 $W/m^{2\circ}C$ at atmospheric pressure for water. Values rise at higher pressure in proportion to the pressure ratio to the power 0.4. (Holman (1976), Jakob and Hawkins (1957)). Perry (1984) quotes values of about 3,000 $W/m^{2\circ}C$ for the overall performance of steam plant using tubes or panels. Increases are achieved if there is a large relative velocity between the source and the sink of heat. (McAdams 1954). Small drops in a steady flow of gas would very quickly be accelerated to the gas velocity but in very turbulent flows the directions of flow would be

reversing. Very much higher heat transfer coefficients, up to 170,000 W/m^2°C, can be achieved for counterflow conditions in spray-towers which have quite similar conditions to the insides of watery explosions. (See Perry (1984) section 21-72.)

Our ignorance of the appropriate value of heat transfer coefficient is matched by our ignorance of the area available for heat transfer. If a volume of liquid Q is broken into spheres of diameter d then the surface area is $6Q/d$. Stokes law for the drag on small spheres and our measurements of the time for the cloud of droplets to fall after an explosion allows us to make an approximate estimate of the range of droplet diameters by equating the Stokes drag force to the gravitational weight of the drop.

EQUATION

If V is the observed velocity of the fall of drops,

μ the viscosity of air = 18 x 10^{-6}Nsec/m^2,

ρ = 1000 and g = 9.81 then the drop diameter d will be

$$d = \sqrt{\frac{18\mu V}{\rho g}}$$

Photographs of the cloud of water after a suppressed explosion show that there are many drops with V less than 2m/sec, giving d less than 2.57×10^{-4} (about 0.01 inch). If a cubic metre of water was divided into drops of this diameter the surface area would be 23,000 square metres. As the rate of evaporation for smaller drops would be proportionately higher, we cannot be sure how many of them may have existed and already been evaporated before the cloud starts to fall. However we can expect that the areas of heat transfer surface will be of the order of some tens of thousands of square metres or perhaps one hundred thousand square metres. Any means by which this could be increased would be beneficial.

It is interesting to ask what breaks up big water droplets. If there is some relative velocity between a drop and the gases around it there will be a 'lift' pressure trying to expand the drop in the direction perpendicular to the relative velocity. This will be resisted by the surface tension of the water. The drop should break if

EQUATION

$$d \geq \frac{8S}{\rho V^2 C_L}$$

where ρ = air density (1.25 kg/m³) d = drop diameter V = relative velocity C_L = lift coefficient and S = surface tension. This has the value of 73 mN/m at room temperature falling to 59 at 100°C and to zero at 374°C.

Without knowing about relative velocities we can still predict that the droplet diameter will fall with reduced surface tension. A small quantity of detergent reduces surface tension by about three.

We can now make some very rough estimates of whether or not there is time for the heat transfer. Suppose that we have a charge weight of 100 kg of TNT with an energy content of 4.52×10^8 joules. We suppress the explosion with 10 tonnes of water broken into drops 0.25 mm in diameter so that the total area is 6 x 10 / 0.00025 = 240,000 m². We can achieve a heat transfer coefficient of 10,000 W/m²°C and guess that the mean temperature in the mixing region is 200°C above the boiling point of the water drops. With these assumptions the entire energy of the explosion would be transferred in only 0.94 milliseconds. This should be long enough without needing arguments about the slower speeds of shock waves in water-gas mixtures. With smaller drops achieved by a surface tension reduction or a higher heat transfer coefficient caused by pressure and the velocity of turbulence, the margin is even greater. Clearly the measurement of these quantities will be of great interest.

The Psychology of Noise Irritation

Engineers usually pay for too little attention to advice from psychologists. In the case of the sound of explosions the opinions of psychologists can be worth many dBs of suppression. It may be helpful to compare two very different cases.

The centre of Edinburgh is dominated by a splendid castle. At exactly 1pm every peacetime day since 1861 with the exceptions of Sundays, Christmas Day and Good Fridays a 25-pounder blank is fired from the parapet. The firing signal is locked to a master clock at Greenwich with a carefully chosen correction for the signal propagation time to Scotland. Although the noise in Princes Street can be quite startling the only complaints ever received have been on the very rare occasions of a misfire. The citizens use the signal to check their watches and find the noise no more irritating than factory sirens or chiming clocks.

East Lothian is a county bordering the city of Edinburgh. Many, far too many, of its farmers own gas guns intended to scare birds away from crops at critical times of their growth. These consist of a cylinder of propane (energy per kg 11 times TNT) which trickles into a barrel at a

controlled rate so as to produce a stoichiometric mixture which is detonated by a spark-plug every few minutes. The equipment is controlled by a time clock but many owners do not set the clocks correctly and so several guns can be heard going off at random intervals through the night and Sunday afternoons. Even if the noise is at the very threshold of hearing it induces murderous feelings among many hundreds of people. These feelings are all the worse because, after a few nights, the birds completely ignore the guns and even learn to associate them with food.

Another point about gun noise is that it is abrupt. This makes it more startling than a noise like the approach of a train which starts quietly and slowly builds up to a crescendo after the subconscious has identified it as harmless. The time integral of the sound power from a train may be much greater than that of the gun but its irritation is very much lower.

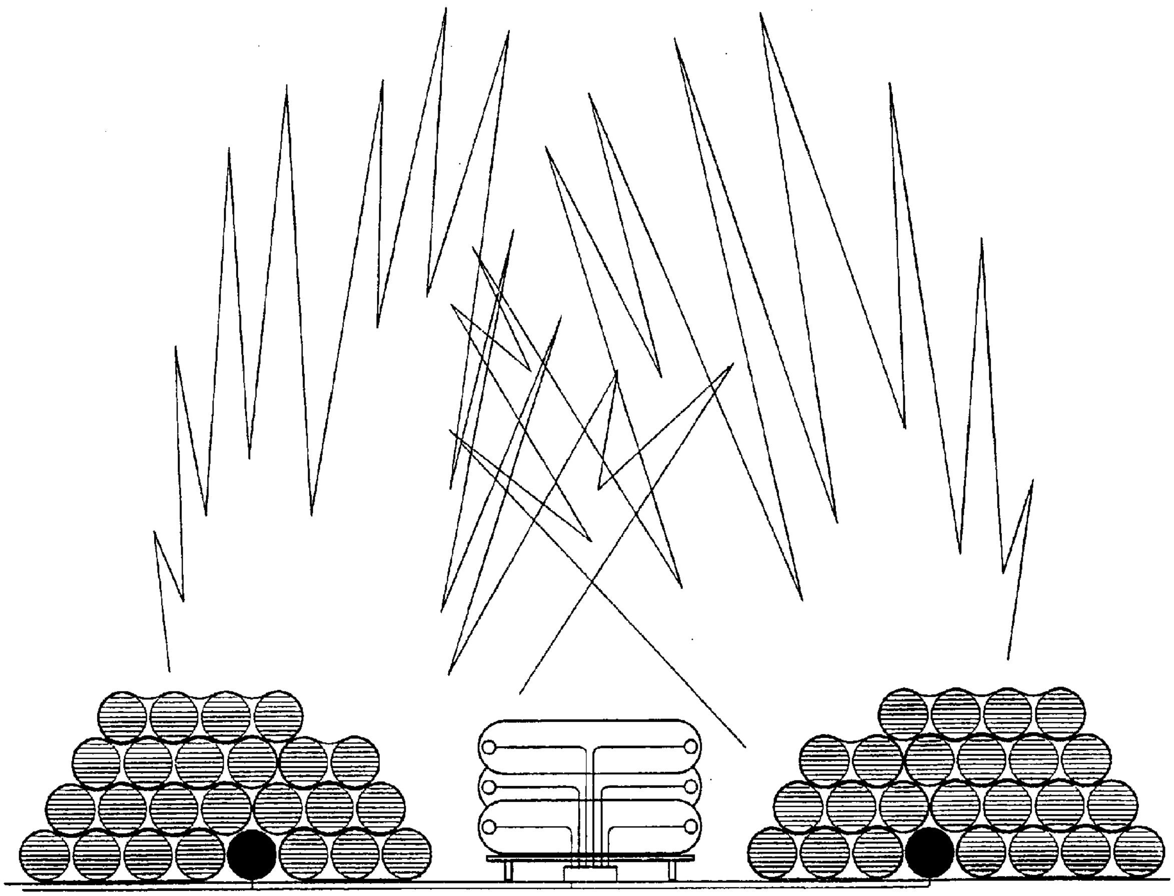
The lesson for military disposal is that you can make a lot of noise provided that you do so at an exact and useful time at the middle of every weekday. If you start quietly you can build up the intensity with an extended series of closely merged explosions lasting for ten seconds or more. This may have implications for very large scale disposal.

Very Large Scale Disposal

One explosive charge inside a set of water bags can be suppressed well. Suppression can be improved by the inclusion of air spaces at carefully chosen points in the pile of bags. But there is a way in which the interaction of hot gases and water droplets can be still further improved. The first problem for the simplest bag arrangement is that when the gases are hottest and when the enhancement of heat-transfer coefficient by high pressure is highest, the surrounding water has not yet been disturbed and so the evaporating surface is still just an expanding shell with a rather low internal area. The second problem is that, later in the process, the water droplets and the cooler gases are moving in more or less the same direction so that the relative velocity is lower than it might be.

For the disposal of many thousands of items of military stores we should be able to achieve much greater reductions by using small suppressed explosions to project large quantities of dispersed water droplets towards larger explosions. The smallest items, perhaps propellants and uncased explosives, would be placed at the perimeter of a large circle and encased in packed water bags with carefully chosen air inclusion. The bags would be arranged in a wider stack on the outside as shown in figure 7. This would bias the water cloud to move towards the centre where there would be the bigger charges such as bombs and larger mines. These would be closely packed, with multiple detonation routes which would be delayed by the fall time of the main body of water. The bigger charges would explode into a deluge of fast, incoming water drops so that the highest pressures and temperatures would occur with maximum counter-flow velocity and large surface area. This should provide even better heat transfer coefficients than those in an industrial spray tower. It is difficult to think of a more satisfactory heat transfer situation.

Figure 7. The use of explosions to suppress explosions. By projecting a cloud of water from small charges at much larger ones we get the ideal combination of the highest pressures, the hottest gases, the largest surface areas and high counter-velocities.



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An even more rapid method of disposal uses the facility sketched in figure 8. This requires a cliff or quarry with a small pond of water at the bottom. At the top of a cliff is a large tank of water built over a short channel. The floor of the tank has a trap door which can be opened to release a deluge of water into the channel and then outwards over the end of the channel and down on top of a charge suspended from two winches a safe distance below. The time of fall of the cloud of water drops can be accurately calculated and so the detonators can be triggered at the correct instant. The dispersed cloud of water drops provides ideal conditions for suppression. The water would run down into the pond and be pumped back to the tank for the next shot. Chemical residues in the water could be neutralised. Soot and scrap steel could be collected. A very similar mechanism built by Heery inc (and designed at Edinburgh University by Matthew Rea) is already in operation not far from here in the Disneyland 'Typhoon Lagoon' at Orlando. This discharges 240 tonnes of water every 90 seconds to make waves for surfers.

If quarries or cliffs are not available we could consider the use of a 'water mortar' . This would consist of a large steel tube with a diameter of about 1 metre and a length of say 10 metres arranged as one edge of a tetrahedron as in figure 9. At the lower end of the tube would be an upward pointing breech, fitted with a glow-plug, into which can be injected propellant fuels at a controlled rate. Propane and compressed-air laced with oxygen would be suitable. Delegates to this conference should not need reminding of the need for the usual non-return valves and left-hand threads to make *absolutely* sure that large volumes of oxygen and propane can never mix at high pressure.

We would partly fill the tube with water and choose the propellant quantities and feed-rates to project water and combustion products to a height of 30 metres or more. A slightly flared blunderbus muzzle would produce a spread discharge. The trajectory of the cloud of water drops would meet clouds from a number of other mortars aimed to converge with the charge just at the moment of detonation. The firing signal could be inhibited if the time integrals of the breech pressures were not all correct.

Disney have not yet acquired the rights to the water mortar but it hard to see how they could resist them!

Figure 8. If a suitable site is available, suppression for long disposal runs can be achieved by dropping water from a safe distance above the charge and then pumping it back to a tank at the top of a cliff. Similar hardware is already in use for making surf waves at Orlando.

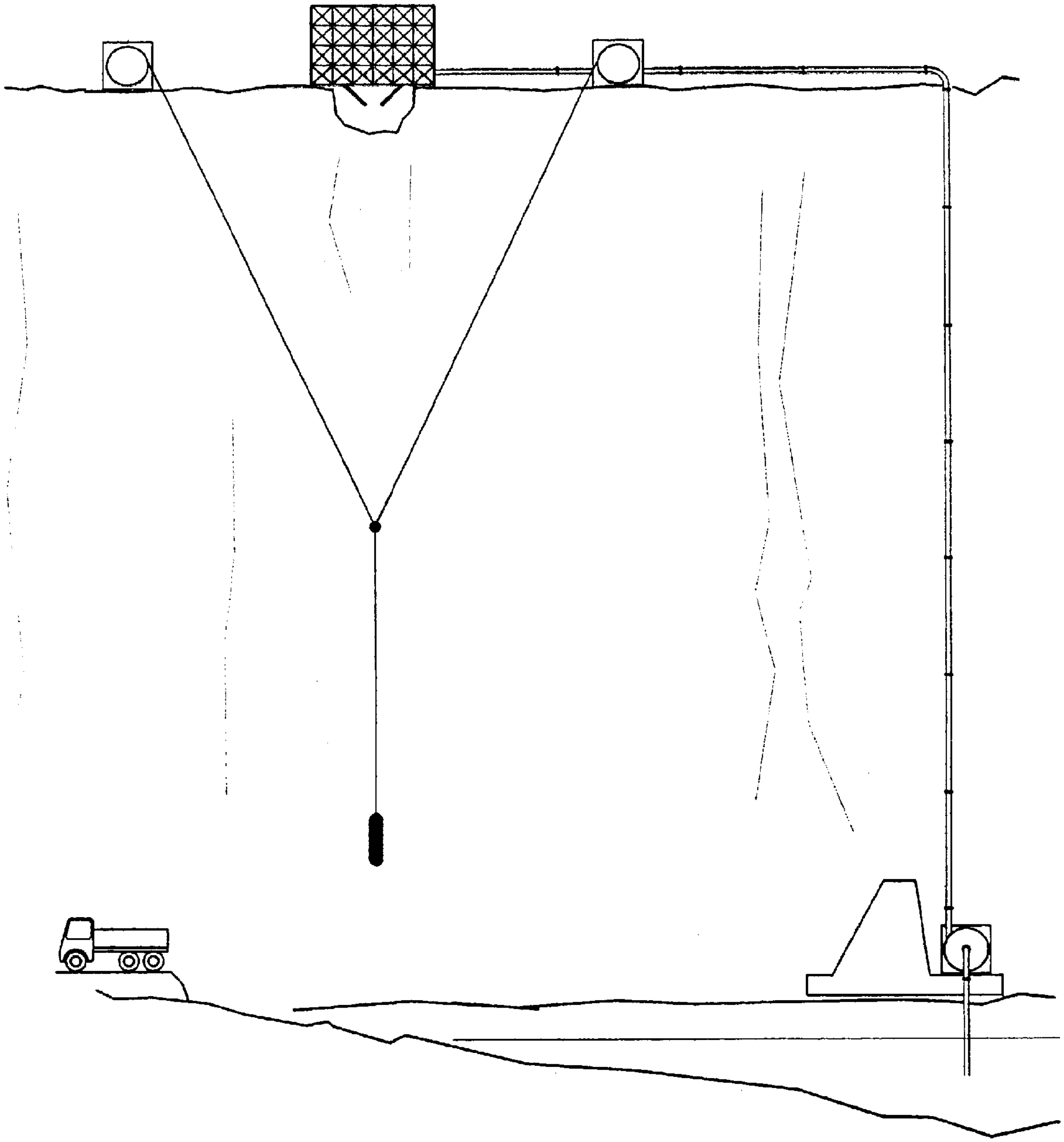

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Figure 9. Water can be thrown at a suspended charge by injecting propellant fuels into the breech of a mortar tube. The necessary pressure is far below anything needed for a gun.

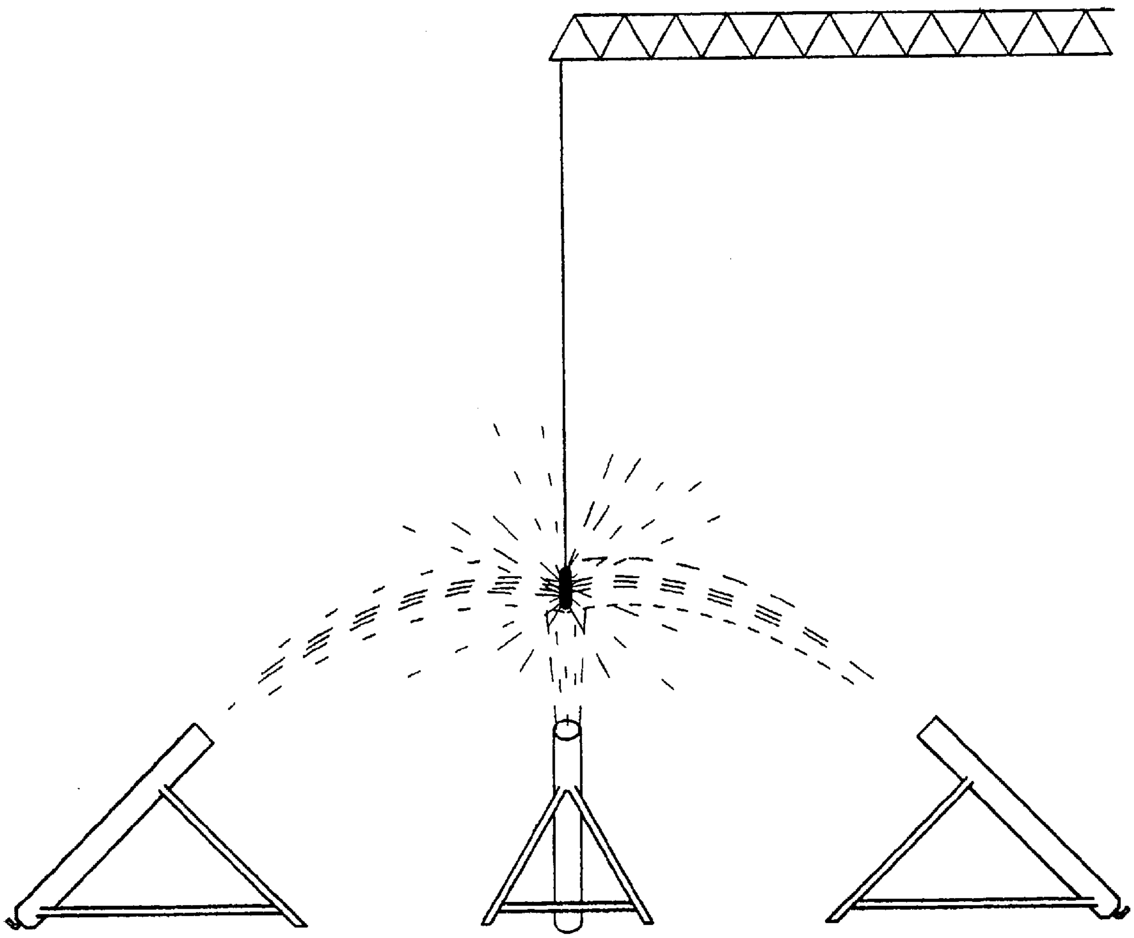

Figure 9. Water can be thrown at a suspended charge by injecting propellant fuels into the breech of a mortar tube. The necessary pressure is far below anything needed for a gun.

Conclusions

Water bags reduce the effects of blast, the speed of blast fragments and the emission of dust. Quite simple bag arrangements can achieve a reduction of sound power and fragment range of about twenty.

The reduction mechanism is partly due to the presence of extra mass to be accelerated and extra drag on fragments but is mainly due to heat removal.

Layflat polythene tubing provides a cheap and convenient material for bag construction.

Water is easier to move than solid materials but single bags are unstable. Stability can be provided by using an outer casing round two or more tubular bags.

Water bags can be used on vertical surfaces spanning a height much greater than the pressure head capability of one bag by arranging them in a cascade over the meshes of a net. Nets and bags are conveniently light for use on outside walls.

The speed of shock waves is reduced by a large factor in mixtures of a liquid and a gas. Air interstices, bubble-pack and air-filled tubes extend the time available for heat transfer and increase the surface area of water drops.

The addition of detergent reduces surface tension and the forces which resist the break up of water drops and so increases the surface area of the water cloud.

Complicated shapes including beams, columns and arches can be built by prefilling bags with air or exhaust gas so as to define a light but rigid structure and then replacing the gas with water. Provided that filling times can be reduced to a few minutes then structures could be placed over suspect car bombs.

For the very large scale disposal of military stores it may be beneficial to use water mortars cliff-top tanks or smaller charges to project water clouds at large charges so that high pressures, high temperatures, large surface areas and high mixing velocities are combined.

The psychology of noise nuisance may be just as important as the engineering of its suppression.

Acknowledgements

We would like to thank the Secretary of State, officials and serving officers in the UK Ministry of Defence for their encouragement and for the promise of explosives and test facilities. This work was stimulated by the deaths of Helen Tinney, a Glasgow housewife who was hit by debris from the demolition of an apartment block and David Miles an experienced explosives engineer who was killed by a high-order detonation while burning jet perforators.

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